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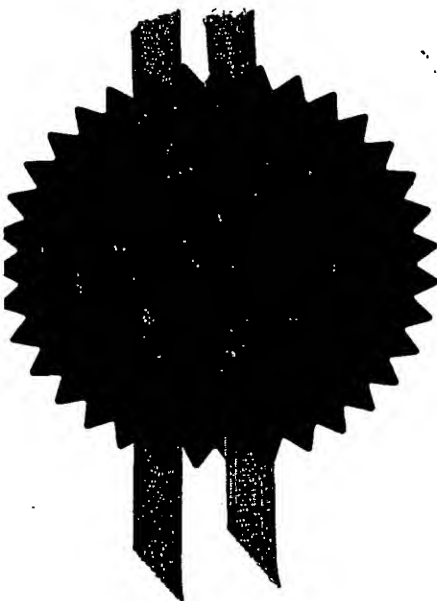
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3. Full name, address and postcode of the or of each applicant (underline all surnames)

**DR DEREK ANTHONY EASTHAM**  
**58 VINCENT DRIVE**  
**CHESTER CH4 7RL**

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

**08403628001**

4. Title of the invention **FOCUSSED ELECTRON and ION BEAMS**

5. Name of your agent (if you have one)

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D. A. Eastham

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D A EASTHAM

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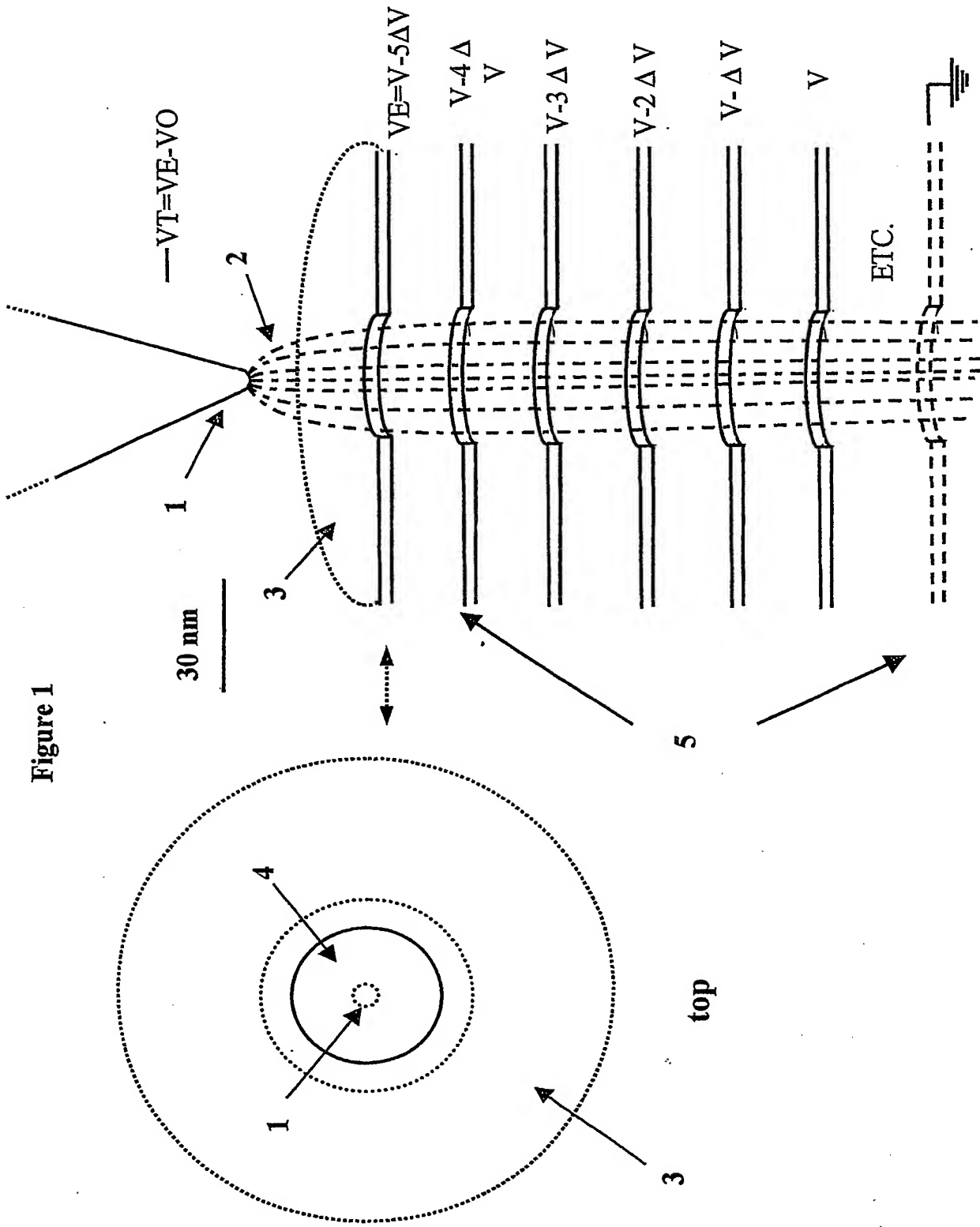


Figure 1

Figure 2

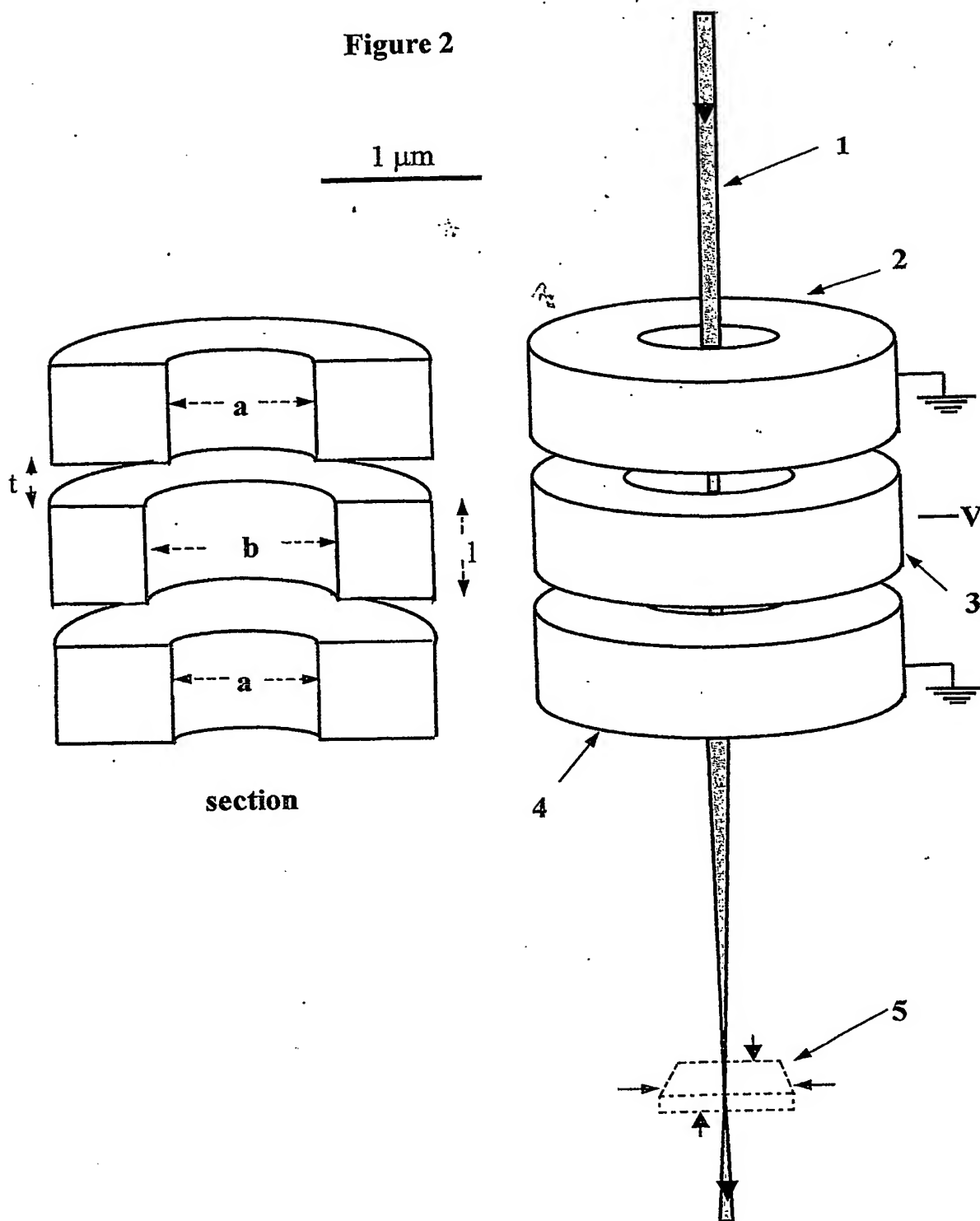
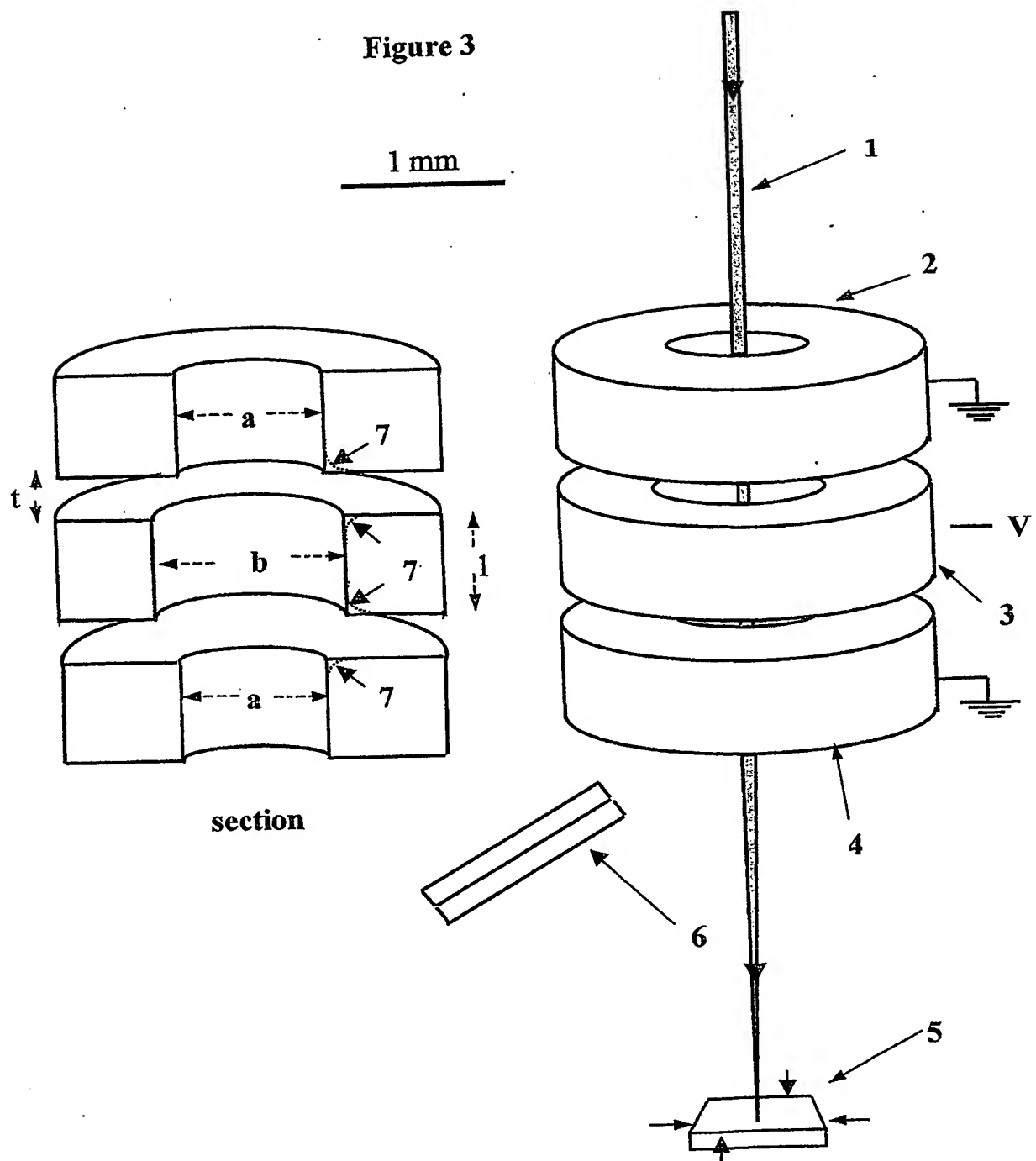


Figure 3



### Focussed Electron and Ion Beams

This present invention relates to the production of focussed electron and ion beams (in vacuum) for use in scanning electron microscopy (SEM) and nanotechnology. In the latter case we are particularly referring to the use of energetic focussed beams for the production of nanostructures and nanostructured surfaces by direct write techniques such as ion beam milling (sputtering), for the case of focussed ion beams (FIB), and surface modification methods, such as polymerisation or oxidation, for electron beams.

The size of the final beam spot and the amount of beam current in this focussed spot determine the performance of these instruments. For microscopy this beam spot size is the effective spatial resolution of the instrument and for nanolithography it determines the minimum size feature which can be made. The current state of the art for commercial electron beam machines is 1 nm for electrons and 30 nm for metallic ion beams. Our designs are capable of superior performance figures than these at a much smaller production cost.

The instruments described here are based on the scale invariance of the ion and electron trajectories in electric and magnetic fields. The absolute size of the beam spot can therefore be related to the overall size (in particular the focal length of the focussing lenses) of the active elements of the instrument. These elements (in order from source to final beam spot) are the ion source assembly, the accelerating section and the lenses used to focus the beam and prevent it from expanding. Our instruments are sub-miniature and contain micro-machined focussing and accelerating sections which prevent the beam expanding. This means that the resolution can be kept much smaller than in larger instruments. Thus a design made at the scale of 100 mm will have beam spot sizes about 100 times larger than a micro-machine with maximum sizes of millimetres. (This is assuming that the geometry is identical apart from scale so that the aberrations in each instrument are the same.) However a larger instrument will allow one to use higher voltages and thus accelerate the beam to higher energies resulting in smaller beam spot sizes. Even when this is taken into account, the beam spot sizes of sub-miniature designs can easily be 10 times smaller than an identical larger instrument.

The first and most essential part of the instrument is the source of electrons/ions. These new designs described here use a nanotip, as employed in near field microscopy techniques such as

scanning tunnelling microscopy (STM). If this nanotip is placed in close proximity to a plate and a voltage is applied between the plate and the tip then electrons can be emitted directly from the tip by the process of field emission. A similar process can produce an ion beam if liquid metal can be supplied to the tip as in focussed ion beam sources. The brightness of these electron/ion beams is extremely large and they can be therefore focussed to small spots. To use this beam and prevent it from expanding we use a plate with a nanoscale aperture in it (extractor electrode) followed by a high electric field region on the side of the plate opposite to the nanotip. Thus the electrons/ions can be successfully extracted from the nanotip and pass through the aperture, which can be centred on the nanotip, by moving the extractor using piezo translation devices as commonly employed in near field spectroscopy. If the electric field on the opposite side of the plate is made to be similar to that on the side facing the nanotip it can both accelerate the electron/ions and at the same time produce a weak focussing effect. The beam size following this aperture is essentially determined by the aperture size and calculations show that most of the electrons or ions emitted from a nanotip can be formed into this beam if the aperture is around 30nm in size.

This design of source is different to that conventional employed in that it uses a nanoscale aperture positioned close to the tip preferably less than a few hundred nanometres away. Thus electrons can be extracted through a minute aperture and can therefore be subsequently confined to small dimensions close to the axis of the following lenses. Also it means that much smaller voltages are needed to generate field emission from the tip. By using a nanoscale/micro-scale accelerating column after the aperture it is possible to generate an approximately equal electric field on either side of the extractor so that is possible for the extractor plate to act as a weak lens. This is in addition to its (the accelerating column) function of accelerating the electrons/ions. Thus the beam is not allowed to expand significantly in its progress through the instrument which has two effects.

- 1) The small radial size of the beam means that the unwanted effects of lens aberrations are small.
- 2) It is possible to use cylindrical focussing lenses (both electrostatic and magnetic) with apertures in the range from 1- 1000 $\mu$ m and thus benefit enormously from the overall decrease in scale of the instrument.

It is important to realise that this novel type of electron/ion source using an apertured extractor plate, but not exclusively, combined with a closely coupled accelerating column is one of the



key elements of this invention. This is because it allows the use of focussing lenses with micro-scale (sub-miniature) and millimetre focal lengths. Since these focal lengths are considerably smaller than conventional electron microscopes it is possible to focus the beam down to much smaller dimensions with fewer corrections for lens aberrations.

These miniature and sub-miniature designs are for operation as stand alone instruments for electron/ion energies up to a maximum of a few keV but they could also be employed as the first stages of a larger conventional high energy electron/ion beam system working up to and beyond 100 keV.

The beam from the source accelerator column then passes through a micro-scale cylindrical einzel lens positioned at a distance such that the beam from the end of the accelerator column has not expanded significantly before it reaches this lens. It is then possible to focus the beam, using this lens, down to diameters below one nanometre at several microns distance from the final lens element. In order to get the smallest focal spot this element is corrected for aberrations by adjusting its geometry as described later.

Although it is possible to use this focussed beam spot directly for SEM or FIB techniques it is more practical if the beam is then passed through a miniature, or sub-miniature, einzel lens with typical aperture diameters from a few hundred to several thousand microns. This lens is positioned at an optimal distance from the first micro lens such that it is possible to obtain the smallest beam spot at distances of millimetres from the end of the last lens element of the lens. Such an arrangement is much more practical and allows for the insertion of electron detectors normally needed for SEM.

Although the beam size through this last lens can be less than a few microns it is still necessary to correct for aberrations (mainly spherical) to achieve the best performance. This is done by altering its geometry as detailed later. Focussed beam spot sizes significantly smaller than 1nm can be obtained if this lens is properly corrected.

A design for a scanning electron microscope which embodies these features is shown in the figures. A diagram for the total working instrument (SEM) is obtained by adding the figures in sequence. The separation of the elements is discussed in the text.

Figure 1 shows the electron source with the extractor and the accelerating column.

Figure 2 is the first cylindrical micro-scale einzel lens which is positioned on the axis of the instrument following the ion source.

Figure 3 is the micro-scale/miniature cylindrical einzel lens positioned on axis after the micro-scale einzel lens. Also shown is the sample holder positioned at the final beam focus.

In fig. 1 the extractor plate 3 is positioned using piezos so that it is located centrally with respect to the nanoprobe 1. The dotted circular line indicates that the extractor plate can be laterally much larger than indicated. The nanoprobe is a standard SEM tip with a radius of around 8nm. The accelerator column 5 consists of a series of aperture plates with circular holes with a common axis in line with the centre of the extractor aperture 4. Each plate is electrically isolated and can be supplied with its own voltage. The voltages on the plates and the nanoprobe are shown on the right hand side for the case of accelerating electrons or negative ions. For this case  $V$  is always negative and the final energy of the electrons from the column is  $VT$  in electron volts (eV).  $\Delta V$  is the voltage difference between each plate in the column and  $VO$  is the difference in voltage between the tip and the extractor plate. (The largest negative voltage is on the tip and the voltages increase moving down the column to the final plate at zero voltage.) The scanning electron microscope shown is designed for operation in the energy range from 300-1000 eV. The voltages and separations of the electrodes are adjusted so that the nanotip emits electrons and the field in the accelerating column is that required to produce a slightly converging beam. Electron trajectories are schematically indicated by the dot/dashed lines with the electrons travelling from the top to the bottom of the figure. These trajectories indicate the overall beam profile which is defined by the envelope which contains the majority of the electrons which are emitted from the tip and pass through the accelerator column. The approximate scale of this particular design is shown at the top.

The first micro-scale lens, which comes after the accelerator column, is shown in fig. 2. and shows the focussing effect on the beam profile 1. This lens is an aberration corrected cylindrical einzel lens consisting of three cylindrical elements 2 3 and 4. The outer two elements are at earth potential and the central element is supplied with a voltage sufficient to focus the electrons at the required position. (Either polarity voltage can be applied but the

aberrations are the smallest for a positive voltage, when used to focus electrons, and a negative voltage when used to focus positively charged ions.) The scale of this particular micro-lens is shown at the top of the figure. The beam is focussed at the sample holder 5 which can be moved laterally to scan the sample and along the beam axis to adjust the focus. The aberrations in this lens are corrected by adjusting the relative dimensions marked a, b, l and t on the section.

Fig. 3 shows the third element of the microscope which comes after the micro-lens. This is a miniature einzel lens. It is essentially the same as the previous lens except that it is approximately a thousand times larger and focuses the beam at a point several millimetres from the end of the instrument where the target 5 is positioned. As previously the scanning is achieved by moving the sample laterally using piezos. Also the holder 5 can be moved along the axis to place the sample at the exact focus. Because the focal length is millimetres it is now possible to include an electron detector in the space above the target. This is used to detect and measure the back-scattered electrons so that scanning images can be obtained. It is most important that this lens is corrected as well as possible for aberrations. In addition to relative adjustments of the dimension a, b, l and t, the curvature of the inner surface 7 shown by a dot/dash line can be also optimally shaped.

### Claims

1. A sub-miniature focussed electron/ion beam machine which can be used for scanning microscopy or nanotechnology, particularly the production of surfaces patterned at nanoscale resolution. These generic machines are essentially micromachines and consist of some or all of the following components.

- i) A nanoprobe (nanotip) source with a 30 nm diameter apertured plate as an extractor and focussing system for the beam.
- ii) A nanoscale accelerating column coming after the extractor to produce an approximately parallel beam of around 30 nm diameter.
- iii) A micro-scale cylindrical einzel lens which is used to focus the previous beam down to sub-nanometre sizes.
- iv) An aberration corrected micro-scale/miniature cylindrical einzel lens used to focus the beam from the micro-scale lens at mm distances from the end of the instrument.
- v) A sample stage on which the target is mounted so that scanning of the sample can be achieved by movement of the sample stage using piezos.
- vi) An electron detector mounted so as to be able to observe the scattered electrons from the sample.

2. A design according to 1 where the plate extractor plate uses a hole size from 5nm to 500 nm. This plate can also be centred relative to the nanotip using piezo translation devices.

3. A design according to 1 which has the accelerating column with an aperture size from 10 nm to 1000  $\mu\text{m}$ . This can also be moved together with the extractor using piezo translators.

4. A design according to 1 which has an accelerating section immediately following the extractor which does not have a column of electrodes but biases the nanotip and extractor plate to higher voltages (negative for electrons and positive for positive ions) whilst preserving the voltage between the nanotip and extractor.

5. A design according to 1 where the aperture of the micro-scale cylindrical lens can have overall dimensions in the range from 1-100  $\mu\text{m}$ .
6. A design according to 1 where the aperture of the miniature einzel lens can have overall dimensions in the range from 0.1 –100 mm.
7. A design according to 1 where the micro-lens is aberration corrected as described earlier.
8. A design according to 1 where the miniature lens is aberration corrected as described earlier.
9. A design according to 1 where the final focus of the beam is between 1 $\mu\text{m}$  and 15 mm from the miniature einzel lens.
10. A design according to 1 where the nanoprobe is fed with liquid metal to enable the instrument to accelerate and focus ion beams instead of electrons.
11. A design where the focused beam is scanned across the sample using electrostatic steerers.
12. A design according to 1 where the einzel lenses are replaced with miniature magnetic lenses.

## ABSTRACT

### Focussed Electron and Ion Beams

The source of electrons is a nanotip in vacuum as used in near field microscopy. The source of ions is a similar nanotip in vacuum supplied with liquid metal (gallium) as in a liquid-metal ion source. Electrons or ions from this nanometre-sized tip are extracted by centralising the tip over an aperture plate and applying a suitable voltage to the tip. The electrons (ions) pass through this plate and are accelerated up to several keV using a nanoscale/microscale accelerating column before being focused using further microscale (or nanoscale) cylindrical lenses. The final element is an aberration corrected miniature (or sub-miniature) einzel lens which can focus the beam at several millimetres from the end of the instrument.

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